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13. ABSTRACT (Maximum 200 words) The bubble departure diameters and bubble emission frequency have been calculated for the nucleate pool boiling data of Engelhorn for many refrigerants over a wide range of heat flux and pressure. The pressure ranged from 0.019 bar to 10.55 bar and the heat flux ranged from 102,000 W/m ² to 1,000 W/m ² . The bubble departure diameters were calculated using Laplace Equation and the bubble emission frequency were calculated using the equations of Sharma et al. The study reveals that the bubble departure diameter increases as the pressure decreases. The bubble emission frequency is the strong function of heat flux. The frequency also increases with increase in pressure, however, not as strong as it increases with heat flux. An increase in the size of the bubble makes the heat transfer process sluggish. An increase in the bubble emission frequency leads to higher heat transfer rates due to enhanced turbulence in the process. Therefore, the heat transfer coefficients are lower at lower pressures and higher at higher pressures and heat fluxes. * Work supported by Army Research Office and Office of Naval Research			
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Enclosure 1

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EFFECT OF PRESSURE AND HEAT FLUX ON BUBBLE DEPARTURE DIAMETERS AND BUBBLE EMISSION FREQUENCY

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INTRODUCTION

Nucleate pool boiling is a very efficient heat transfer process for removing heat from a heat transfer surface. It is one of the important mechanisms to remove heat from electronic and microelectronic equipment, nuclear reactors, space vehicles, and other heat transfer equipment used in process, refrigeration, and food industry. In order to understand the process of heat transfer it is important to understand the underlying mechanism of the process. An analytical model consistent with the requirements of nucleate pool boiling heat transfer requires mathematical expressions for:

- 1) Number of Nucleation Sites**
- 2) Bubble Departure Diameters**
- 3) Bubble Growth Rates**
- 4) Bubble Emission Frequency**

The purpose of this work is to calculate the bubble departure diameters and bubble emission frequency for the data of Engelhorn. Engelhorn has conducted experiments for a wide variety of refrigerants and for a wide range of heat flux and pressure. For the calculation of bubble departure diameters we used Laplace Equation and for the bubble emission frequency we used the equations earlier developed by Sharma et al.

ANALYSIS:

Bubble Departure Diameter

The bubble departure diameters are obtained by analyzing the forces on a typical growing bubble. Two forces are important; surface tension and the buoyancy.

$$\text{Surface Tension Force} = \pi D \sigma$$

$$\text{Buoyancy Force} = \frac{\pi}{6} D^3 [\rho_1 - \rho_v] g$$

At equilibrium, the two forces are equal.

$$\frac{\pi}{3} D^3 [\rho_1 - \rho_v] g = \pi D \sigma$$

$$D = C \sqrt{\frac{\sigma}{[\rho_1 - \rho_v] g}} \quad (1)$$

Equation (1) is known as the Laplace Equation. The equation shows that bubble departure diameters is the function only of physical properties which are constant for a given pressure.

Bubble Emission Frequency

In nucleate pool boiling heat transfer, bubble emission frequency (f) is composed of two periods;

- 1) Growth period (θ_d) and 2) Waiting period (θ_w)

Therefore, bubble emission frequency f is:

$$f = \frac{1}{(\theta_d + \theta_w)}$$

The equations were earlier developed for the growth period and the waiting period. From those equations, the final equations for the bubble emission frequency are:

for $Ja \leq 100$

$$f = \frac{1}{\frac{[133.3/P]^2 [\sigma/(\rho_1 - \rho_v)g]}{\pi \alpha_1 Ja^2} + \frac{0.867}{\alpha_1} \left[\frac{k \Delta T_w}{q_w} \right]^2}$$

and for $Ja > 100$

$$f = \frac{1}{\frac{[133.3/P]^2 [\sigma/(\rho_1 - \rho_v)g]}{25 \alpha_1 Ja^{3/2}} + \frac{0.867}{\alpha_1} \left[\frac{k \Delta T_w}{q_w} \right]^2}$$

The above equations reveal that for a given liquid and at a given pressure the bubble emission frequency is a function of heat flux, and physico-thermal properties . These equations were used to calculate the bubble emission frequency for the data of Engelhorn.

RESULTS

The bubble emission frequency were calculated for refrigerants R-11, R-12, R-13, R-13B1, and R-22. Table-1 shows the values of pressures for each fluid and the range of heat flux.

TABLE-1

REFRIGERANTS	HEAT FLUX, W/m ²	PRESSURE, Bar
R-11	1,000 to 83,000	0.019,0.028, 0.503, & 0.991
R-12	100 to 102,000	0.25, 0.50, 1.0 &1.80
R-13	200 to 84,000	2.80, 4.55, 7.35 &10.55
R-13B1	200 to 96,000	0.78,1.51& 5.60
R-22	200 to 99,000	0.39,0.84 & 2.15

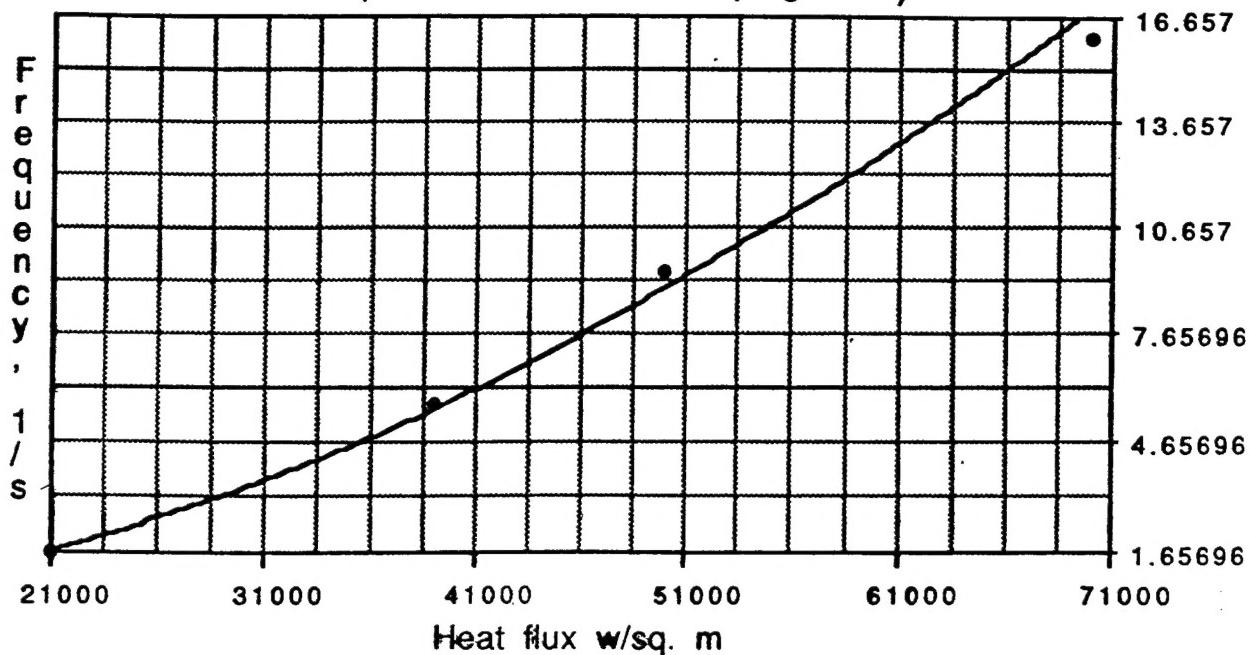
Graphs were prepared for the frequency as a function of heat flux. The study reveals that bubble frequency is the strong function of heat flux. It increases with increase in heat flux. The inspection of these graphs also reveal that bubble frequency also is a function of pressure. An increase in pressure shows increase in bubble emission frequency. An increase in bubble emission frequency with increase in heat flux and pressure implies that heat transfer rates in boiling will be enhanced with increase in heat flux and pressure.

The calculations also reflect the effect of pressure on bubble departure diameter. The bubble departure diameters decrease with increase in pressure. This functional relationship is shown by making plots of bubble departure diameter as a function of pressure for five refrigerants investigated. The increase in the bubble departure diameter with decrease in pressure will manifest as reduction in heat transfer coefficients as pressure decreases.

CONCLUSIONS

- 1.** The study reveals that the bubble emission frequency is a strong function of heat flux. It also increases with increase in pressure.
- 2.** Bubble departure diameters are the function only of pressure for a given liquid. The bubble departure diameter decreases with increase in pressure.

f vs q at 0.019 bar for R-11(Engelhorn)



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Power Curve Fit

Pts Plotted = 4

Offscale Pts = 0

Regression Equation:

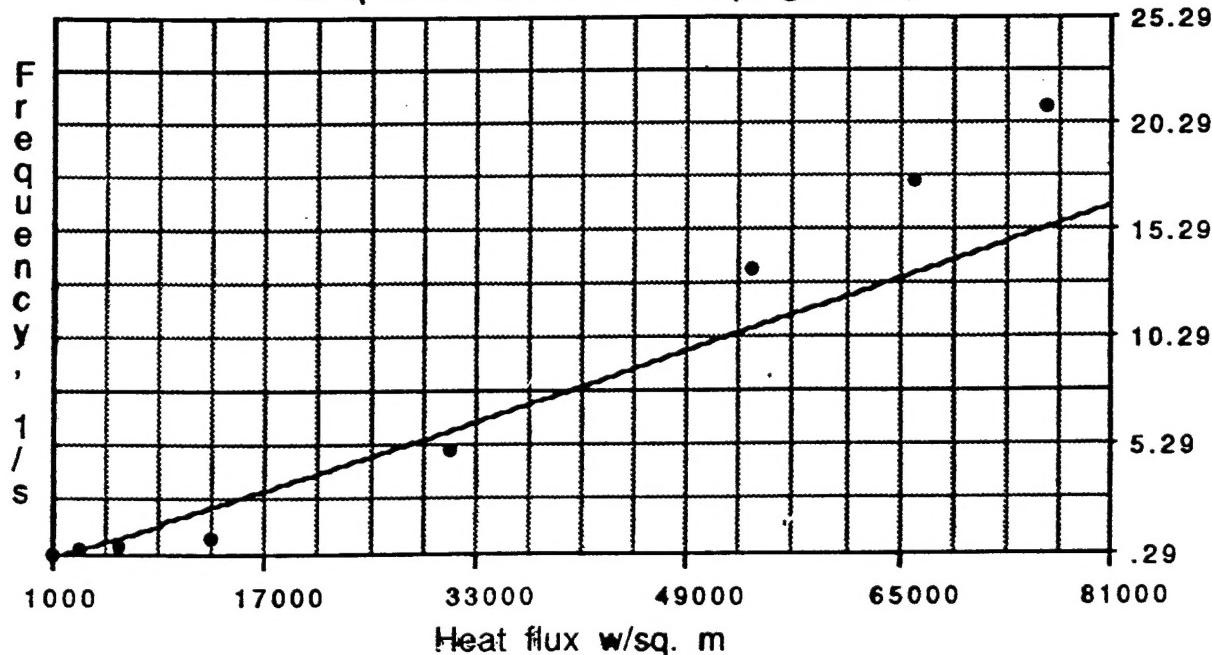
$$Y = 9.80831 \times 10^{-9} X^{1.90664}$$

Correlation Coefficient = .998636

X-axis file: r11_heatflux_1

Y-axis file: r11_freq_1

f vs *q* at 0.028 bar for R-11(Engelhorn)



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Power Curve Fit

Pts Plotted = 8

Offscale Pts = 0

Regression Equation:

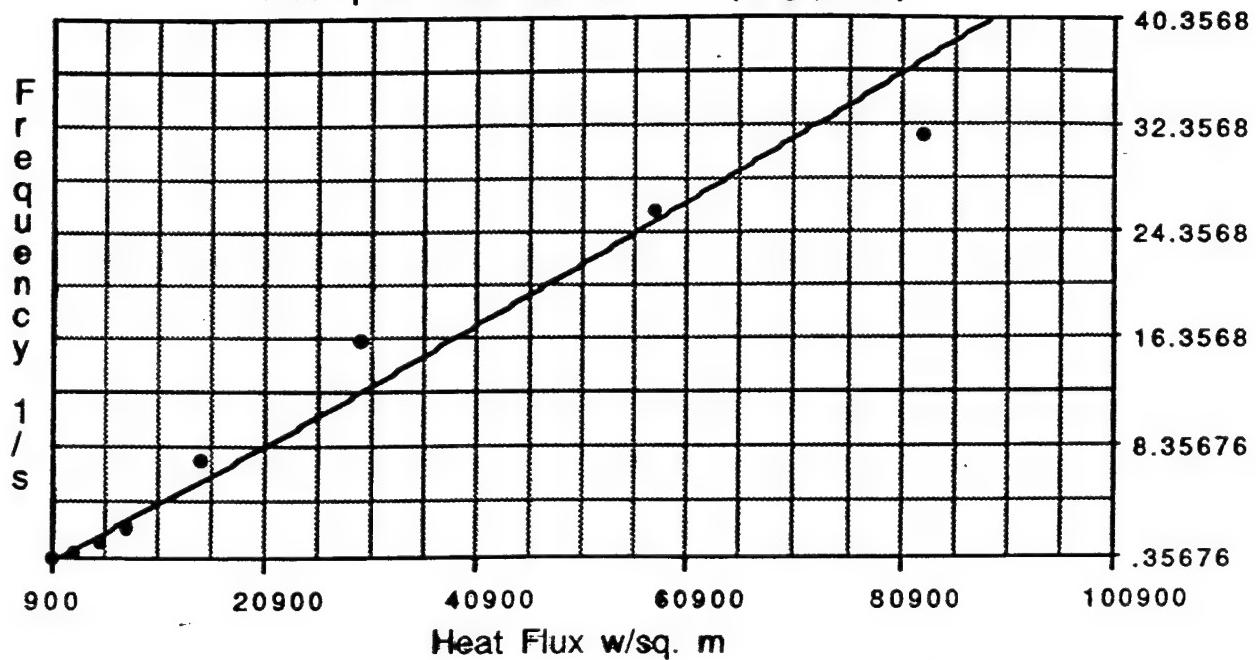
$$Y = 1.03267E-04 X ^ 1.05954$$

Correlation Coefficient = .96324

X-axis file: r11_heatflux_2

Y-axis file: r11_freq_2

f vs *q* at 0.503 bar for r-11 (Engelhorn)



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Power Curve Fit

Pts Plotted = 8

Offscale Pts = 0

Regression Equation:

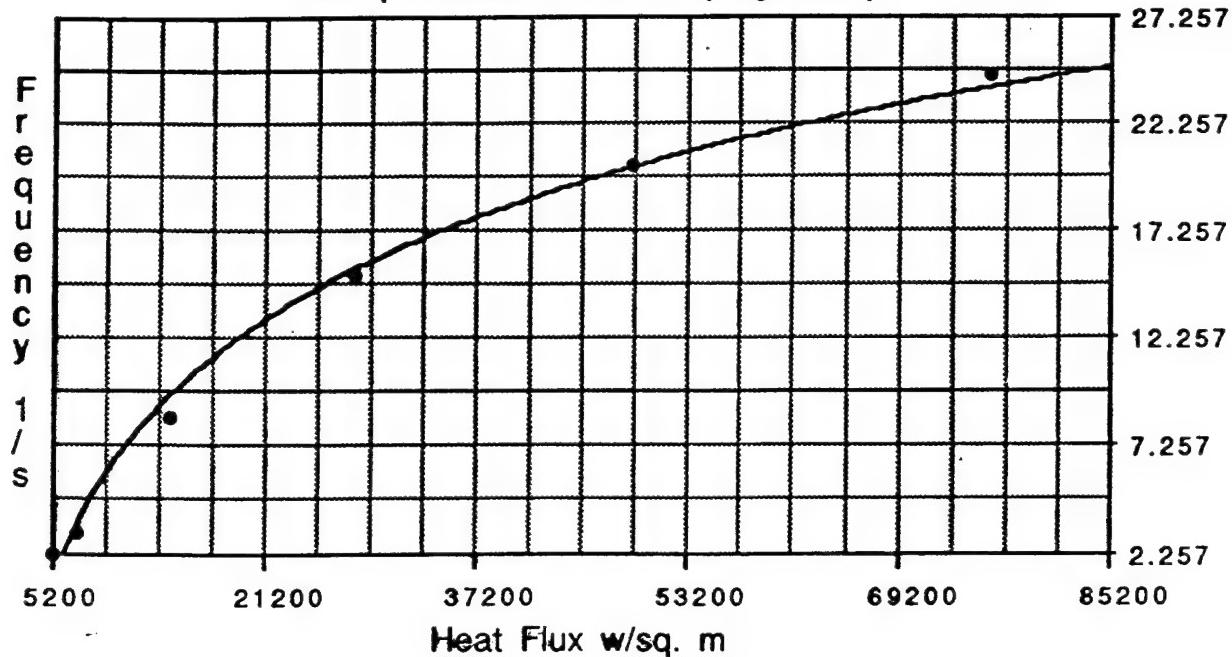
$$Y = 1.7335E-04 X ^ 1.08382$$

Correlation Coefficient = .990954

X-axis file: r-11_q_x-axis

Y-axis file: r-11_f_y-axis_0.503

f vs q at 0.991 for R-11 (Engelhorn)



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Logarithmic Curve Fit

Pts Plotted = 6

Offscale Pts = 0

Regression Equation:

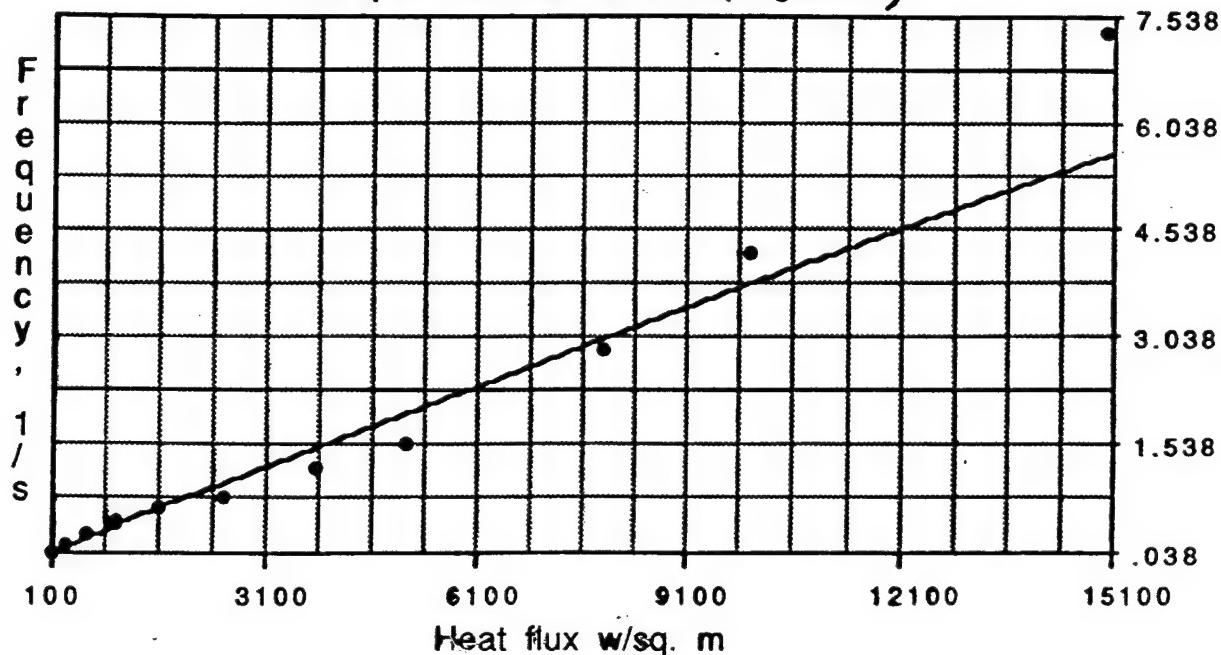
$$Y = -71.4429 + (8.48594) \text{ LNX}$$

Correlation Coefficient = .99651

X-axis file: r-11_0.991_x-axis

Y-axis file: r-11_0.991_f_y-axis

f vs q at 0.25 bar for R-12(Engelhorn)



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Power Curve Fit

Pts Plotted = 11

Offscale Pts = 0

Regression Equation:

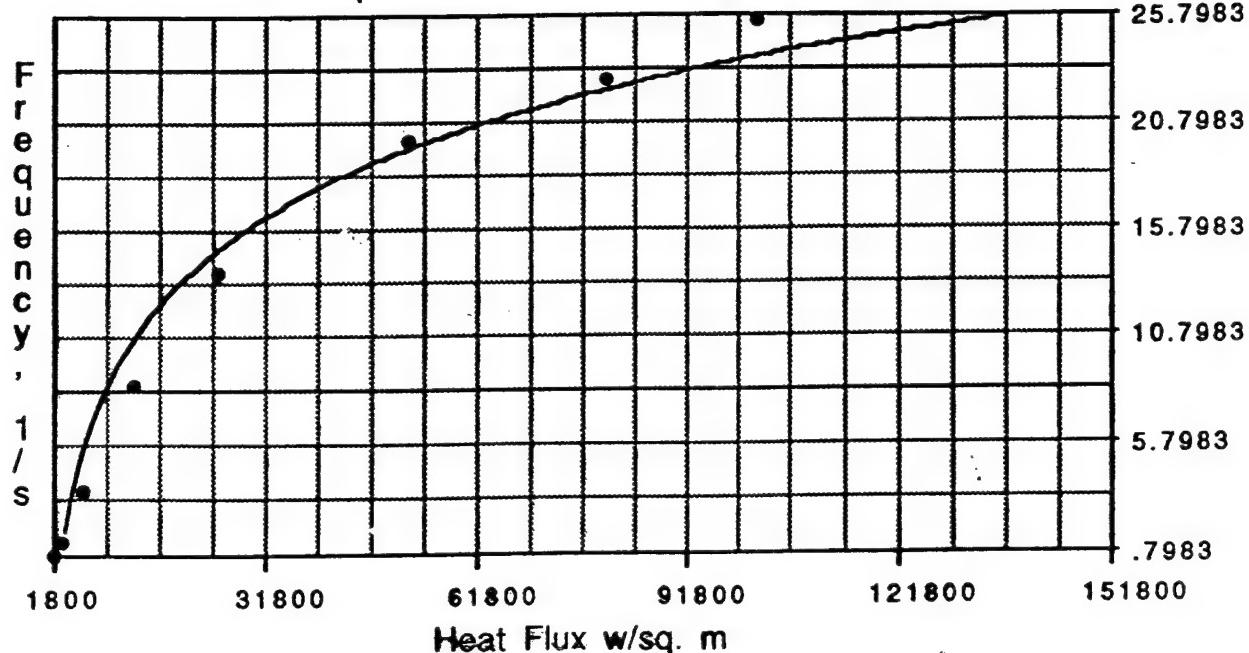
$$Y = 4.98357E-04 X ^ {.969699}$$

Correlation Coefficient = .992982

X-axis file: r12_heatflux_1

Y-axis file: r12_freq_1

f vs q at 1.00 bar for R-12 (Engelhorn)



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Logarithmic Curve Fit

Pts Plotted = 8

Offscale Pts = 0

Regression Equation:

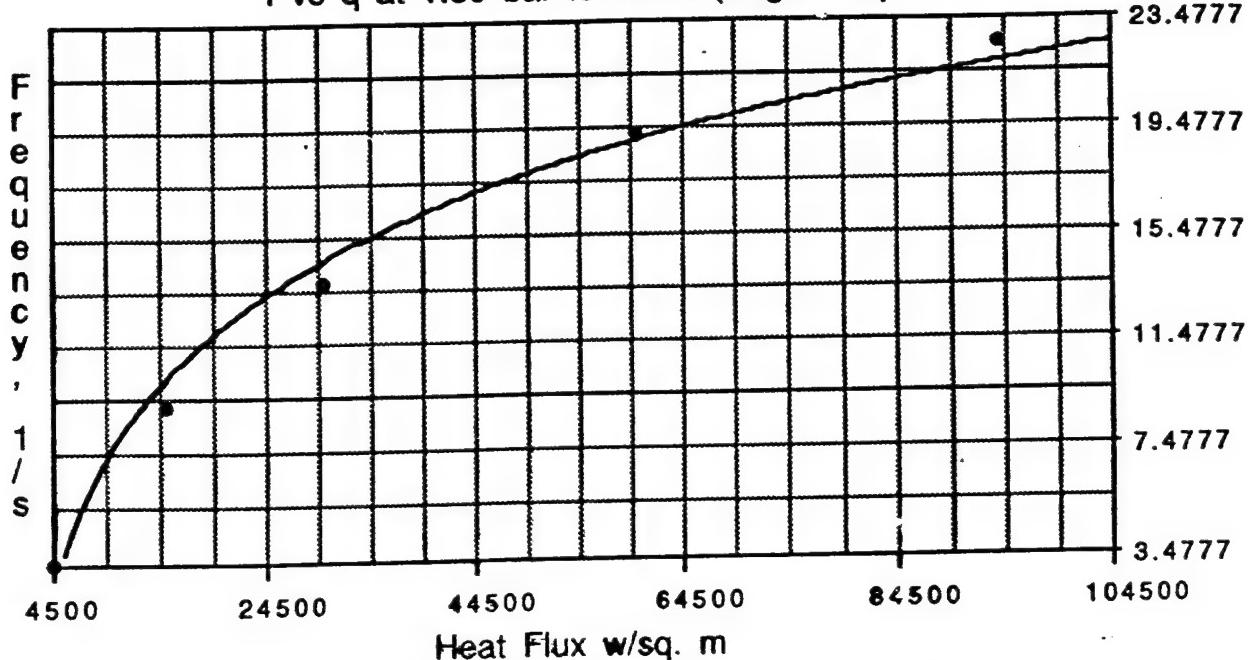
$$Y = -49.7848 + (6.38598) \ln X$$

Correlation Coefficient = .984858

X-axis file: r12_heatflux

Y-axis file: r12_freq

f vs *q* at 1.80 bar for R-12 (Engelhorn)



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Logarithmic Curve Fit
Pts Plotted = 5

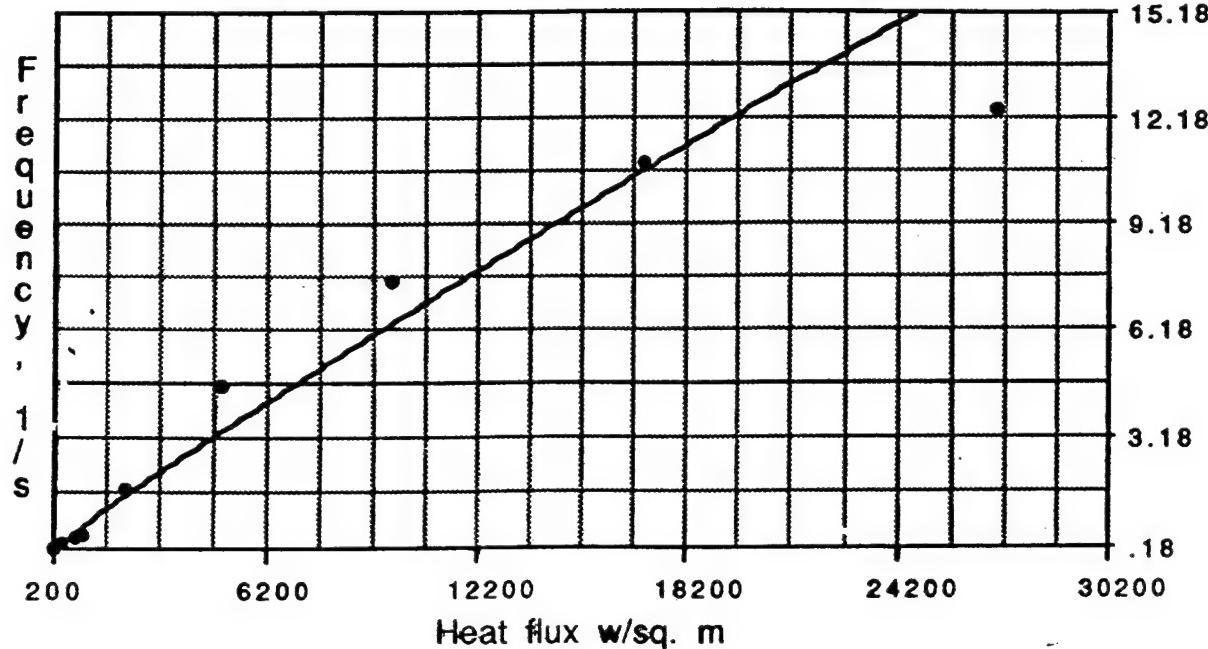
Offscale Pts = 0

Regression Equation:
 $Y = -50.8725 + (6.3533) \ln X$

Correlation Coefficient = .993208

X-axis file: r12_heatflux2
Y-axis file: r12_freq2

f vs q at 2.8 for R-13 for the Data of Engelhorn



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Power Curve Fit

Pts Plotted = 9

Offscale Pts = 0

Regression Equation:

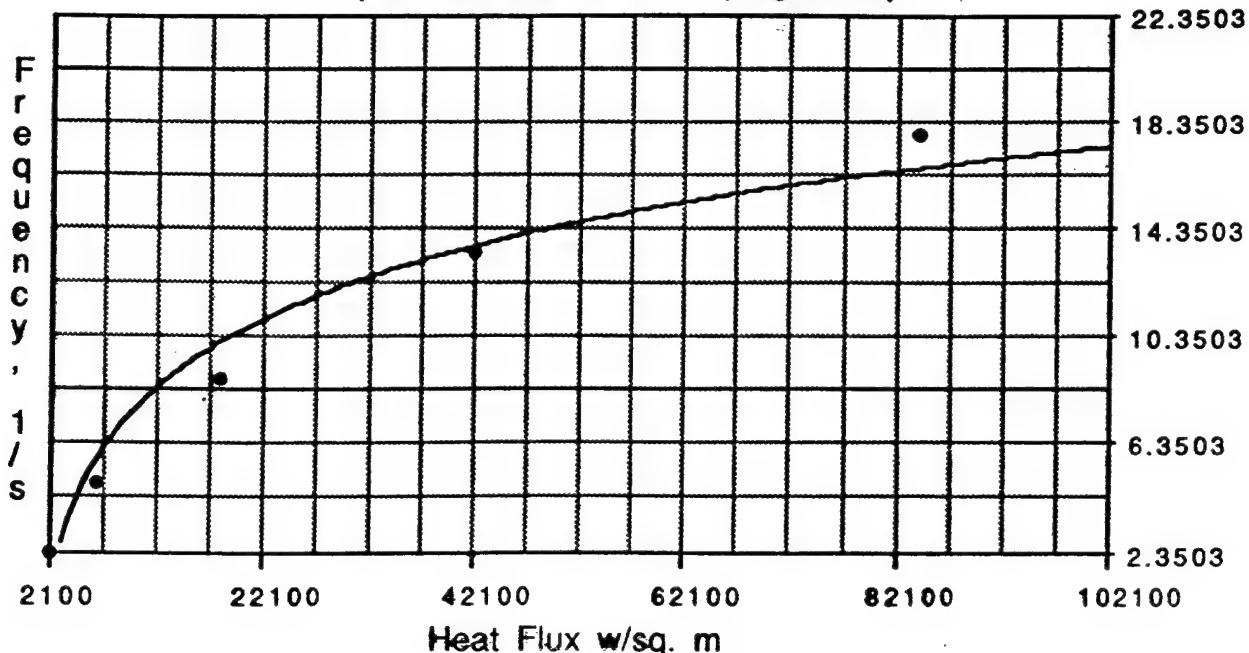
Y = 1.15874E-03 X ^ .93721

Correlation Coefficient = .99093

X-axis file: r13_heatflux_1

Y-axis file: r13_freq_1

f vs q at 4.55 bar for R-13 (Engelhorn)



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Logarithmic Curve Fit

Pts Plotted = 5

Offscale Pts = 0

Regression Equation:

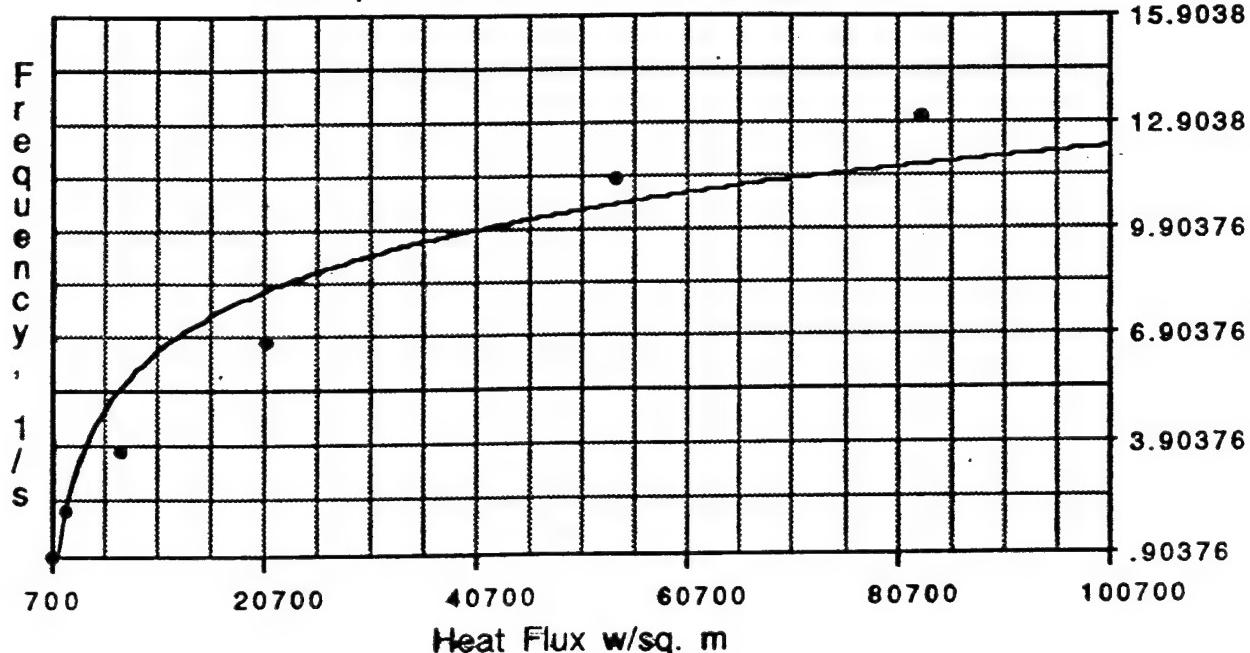
$$Y = -31.0799 + (4.20439) \ln X$$

Correlation Coefficient = .981057

X-axis file: r12_heatflux1

Y-axis file: r13_freq1

f vs q at 7.35 bar for R-13 (Engelhorn)



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Logarithmic Curve Fit

Pts Plotted = 6

Offscale Pts = 0

Regression Equation:

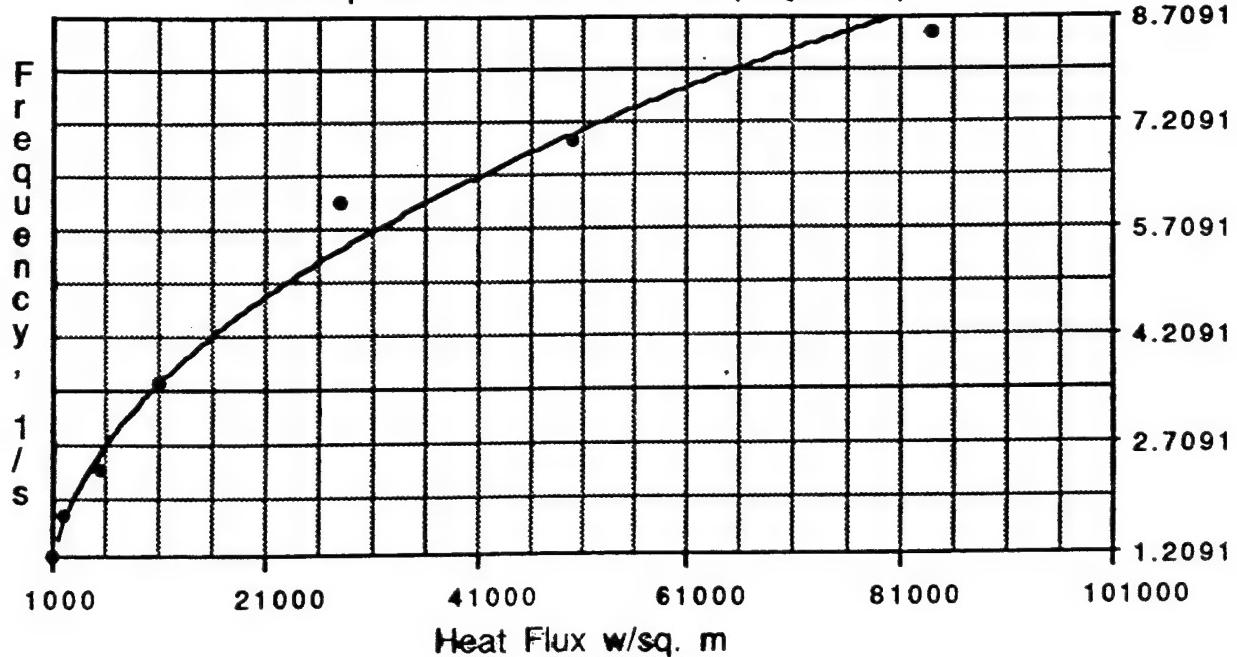
$$Y = -17.1613 + (2.54968) \ln X$$

Correlation Coefficient = .960946

X-axis file: r13_heatflux2

Y-axis file: r13_freq2

f vs q at 10.55 bar for R-13 (Engelhorn)



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Power Curve Fit

Pts Plotted = 7

Offscale Pts = 0

Regression Equation:

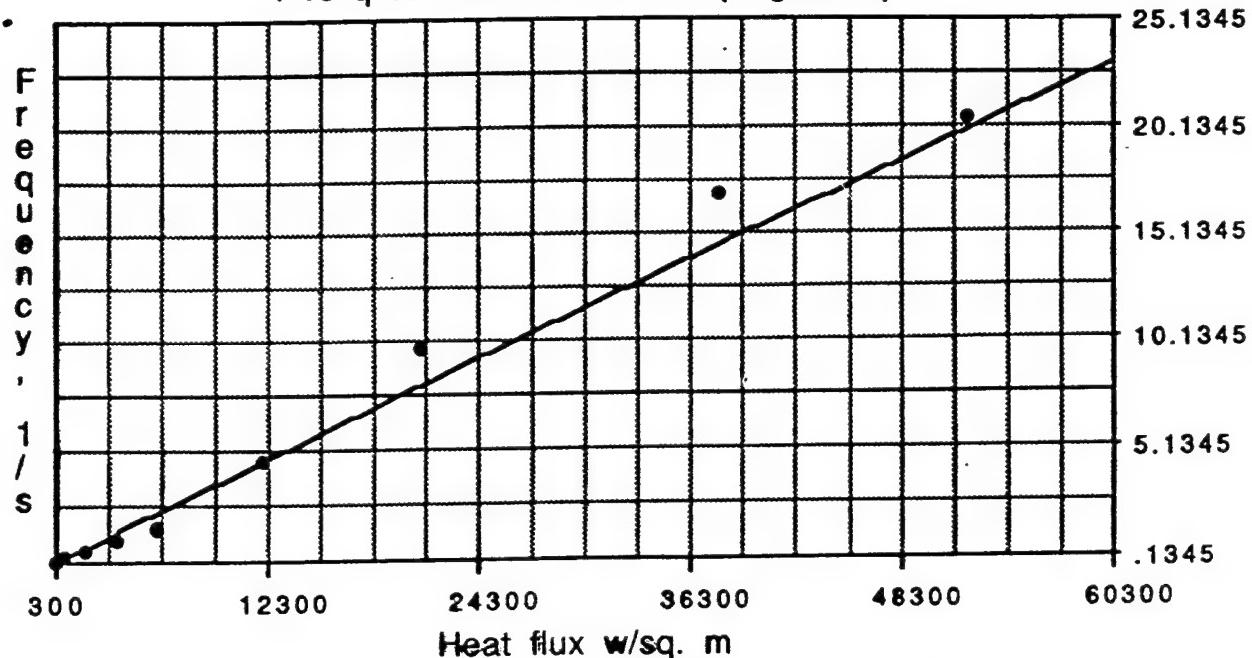
$$Y = 5.35501E-02 X ^ .450906$$

Correlation Coefficient = .996364

X-axis file: r13_heatflux3

Y-axis file: r13_freq3

f vs q at 0.39 bar for R-22(Engelhorn)



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Power Curve Fit
Pts Plotted = 9

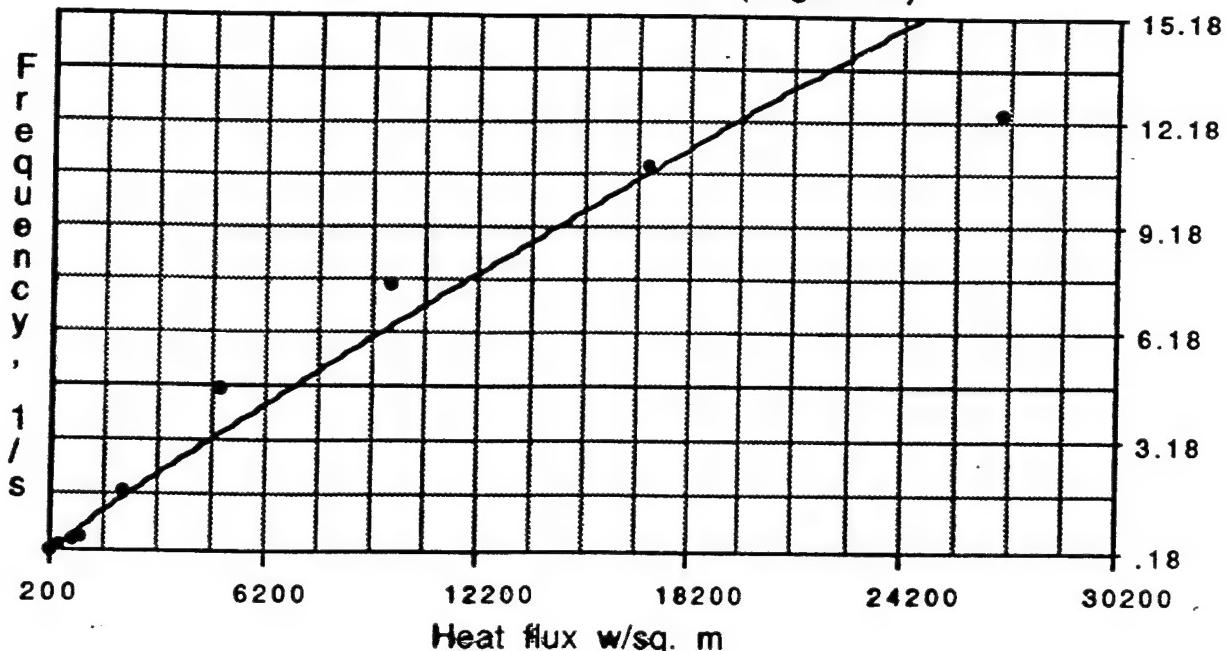
Offscale Pts = 0

Regression Equation:
 $Y = 3.8682E-04 X ^ .999344$

Correlation Coefficient = .99372

X-axis file: r22_heatflux_1
Y-axis file: r22_freq_1

f vs *q* at 0.78 bar for R-13b1(Engelhorn)



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Power Curve Fit

Pts Plotted = 9

Offscale Pts = 0

Regression Equation:

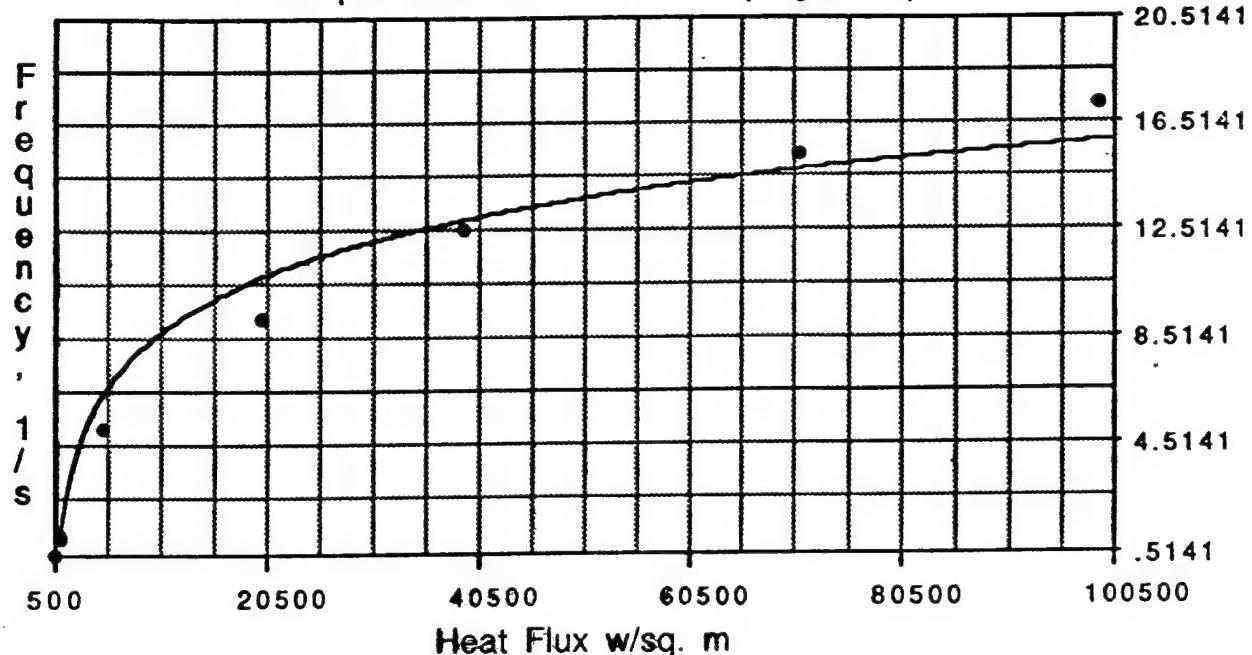
$$Y = 1.15874E-03 X ^ {.93721}$$

Correlation Coefficient = .99093

X-axis file: r13_heatflux_1

Y-axis file: r13_freq_1

f vs q at 5.60 bar for R-13b1 (Engelhorn)



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Logarithmic Curve Fit

Pts Plotted = 7

Offscale Pts = 0

Regression Equation:

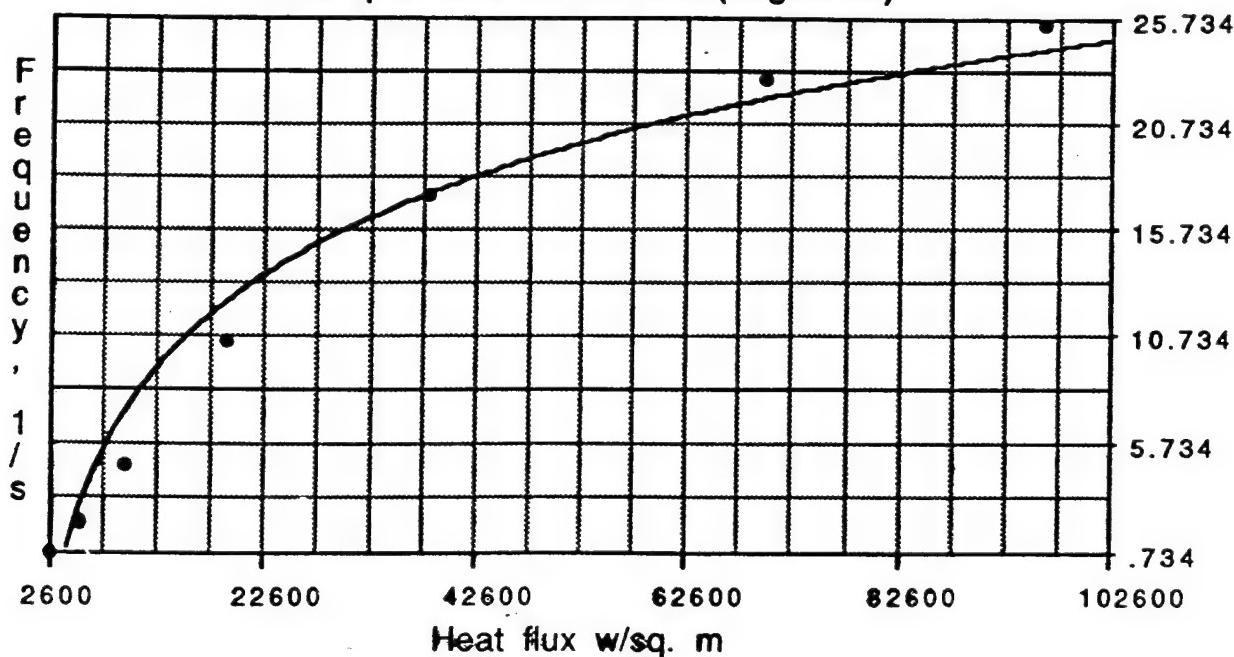
$$Y = -20.435 + (3.15063) \ln X$$

Correlation Coefficient = .984194

X-axis file: r13b1_heatflux2

Y-axis file: r13b1_freq2

f vs q at 0.84 bar for R-22(Engelhorn)



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Logarithmic Curve Fit

Pts Plotted = 7

Offscale Pts = 0

Regression Equation:

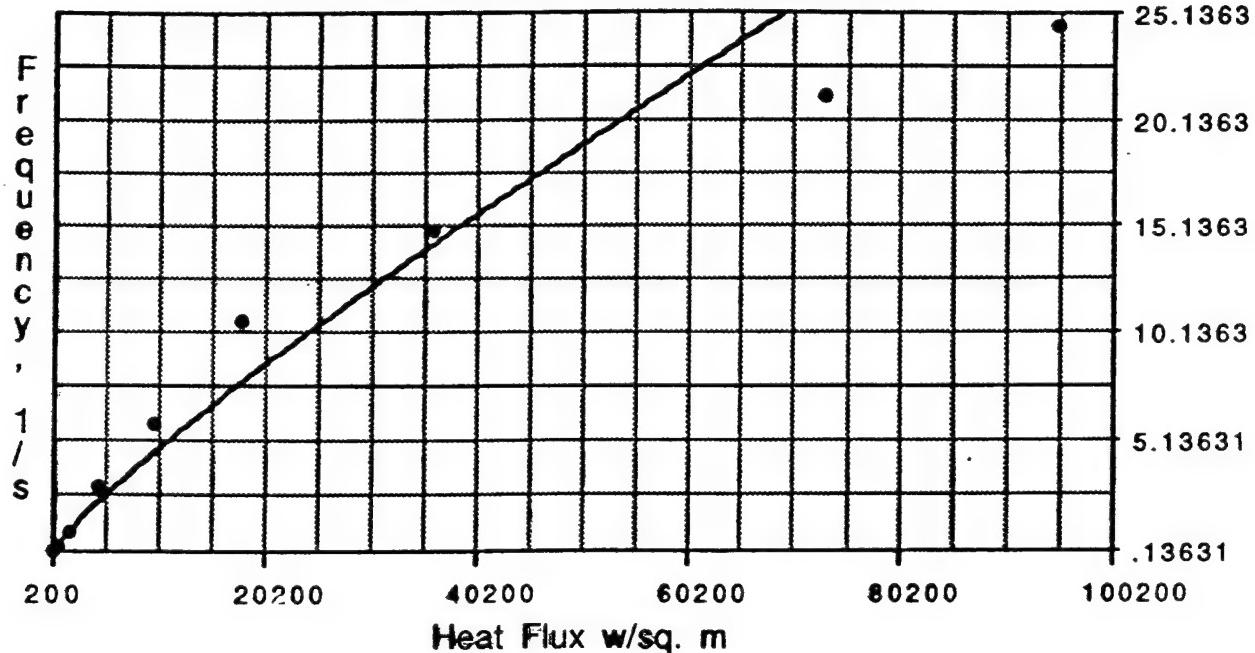
$$Y = -60.4545 + (7.38578) \ln X$$

Correlation Coefficient = .981094

X-axis file: r22_heatflux_2

Y-axis file: r22_freq_2

f vs q at 2.15 bar for R-22 (Engelhorn)



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Power Curve Fit

Pts Plotted = 9

Offscale Pts = 0

Regression Equation:

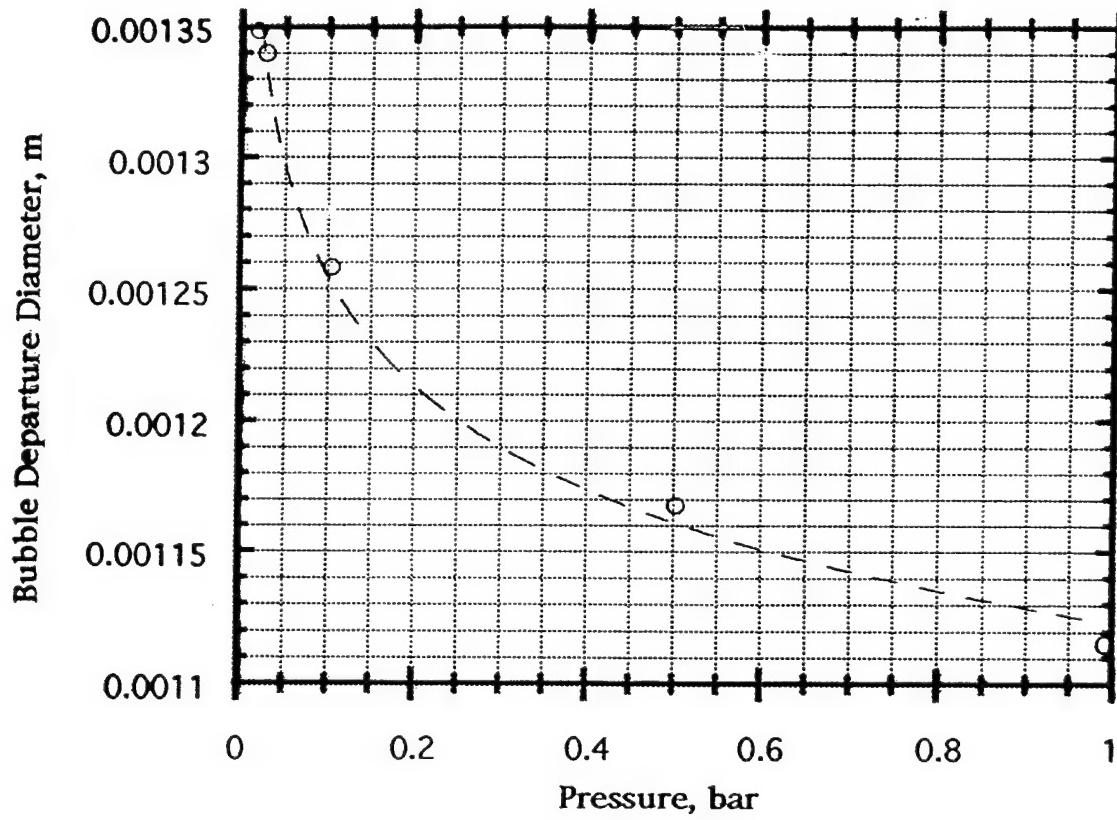
$$Y = 1.61784E-03 X ^ {.865801}$$

Correlation Coefficient = .992676

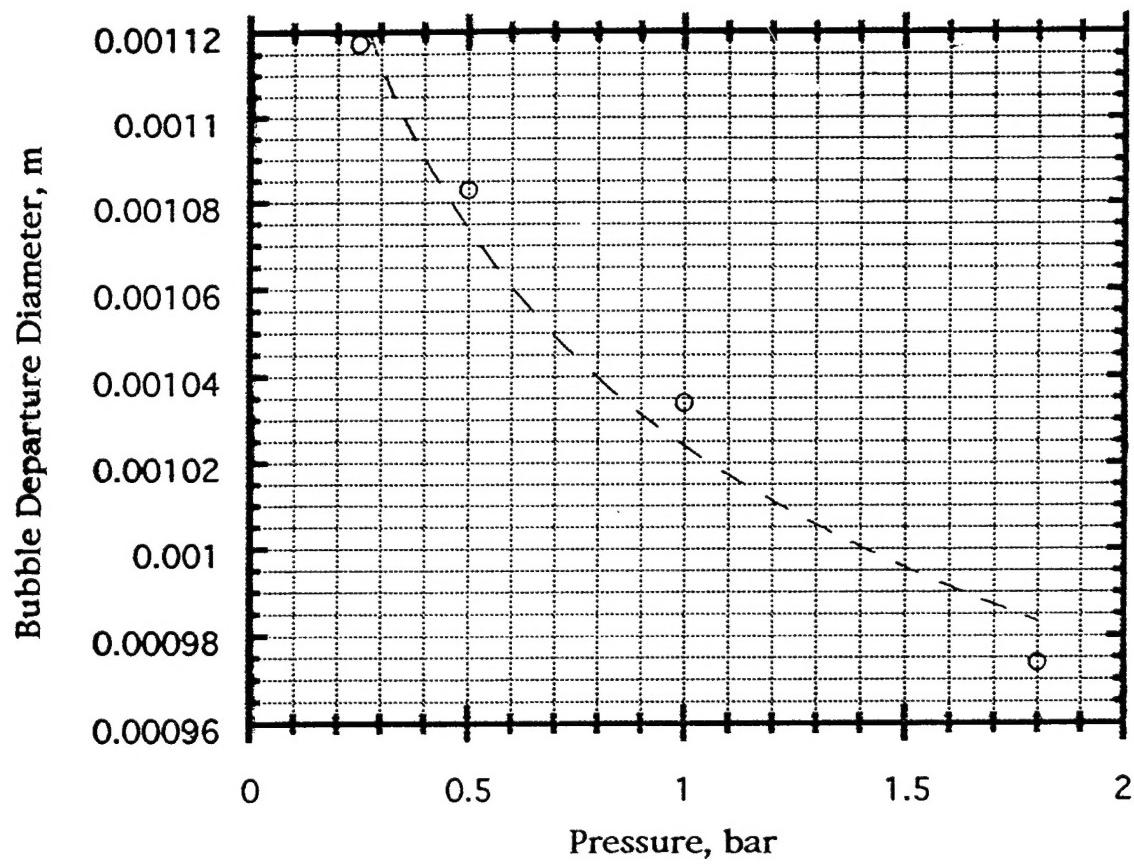
X-axis file: r22_heatflux

Y-axis file: r22_freq

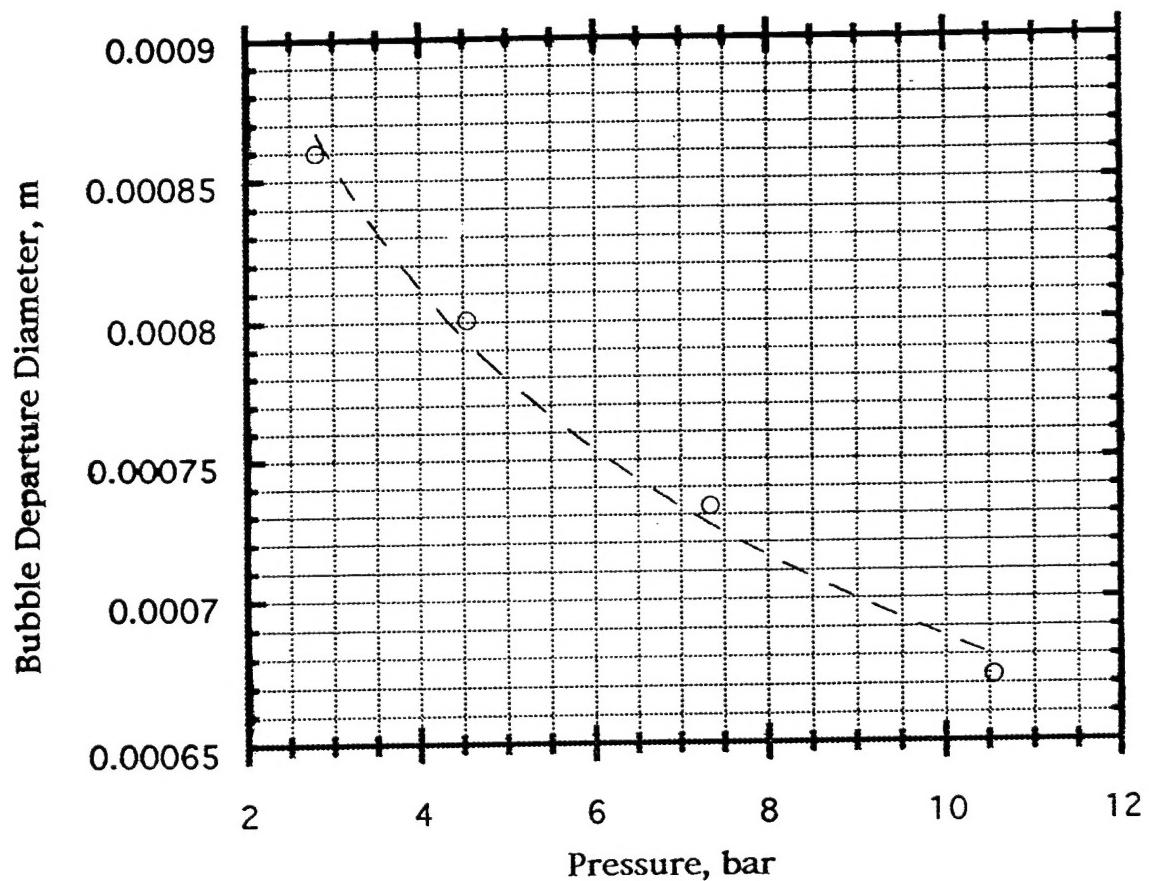
Pressure vs Departure Diameter for R-11 (Data of Engelhorn)



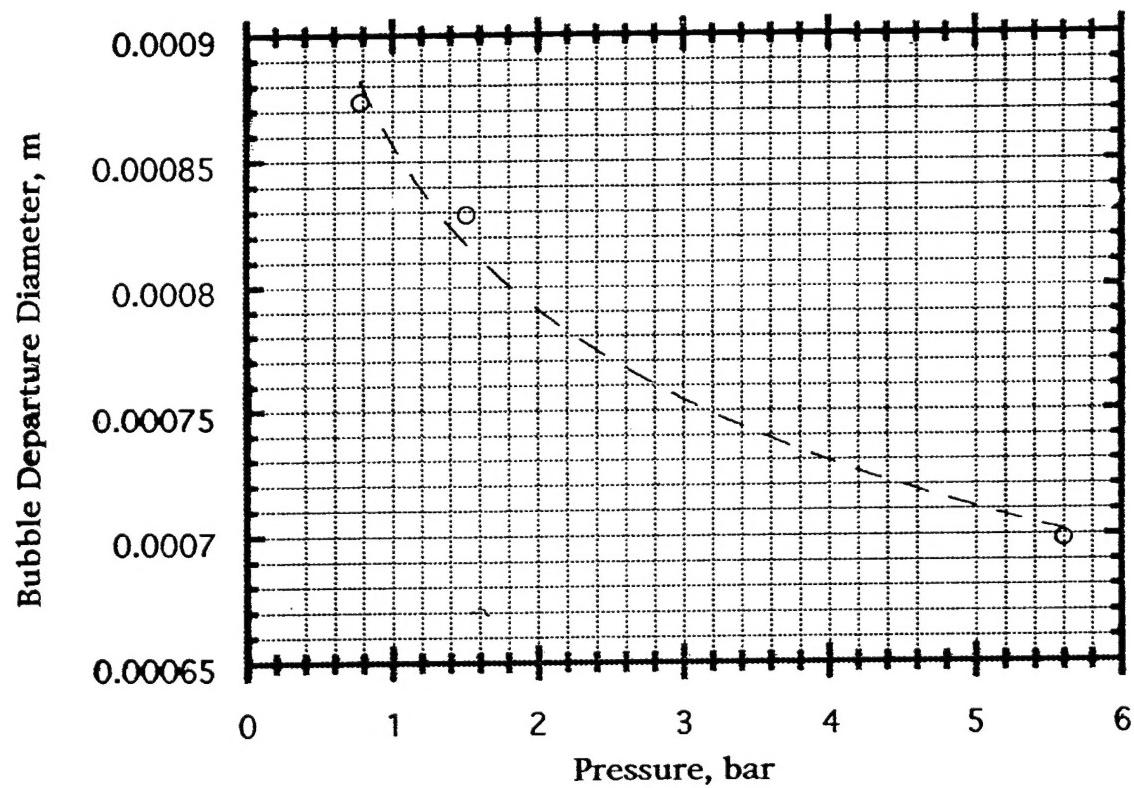
Pressure vs Departure Diameter for R-12
(Data of Engelhorn)



Pressure vs Departure Diameter for R-13 (Data of Engelhorn)



Pressure vs Departure Diameter for R13B1 (Data of Engelhorn)



Pressure vs Departure Diameter for R-22 (Data of Engelhorn)

